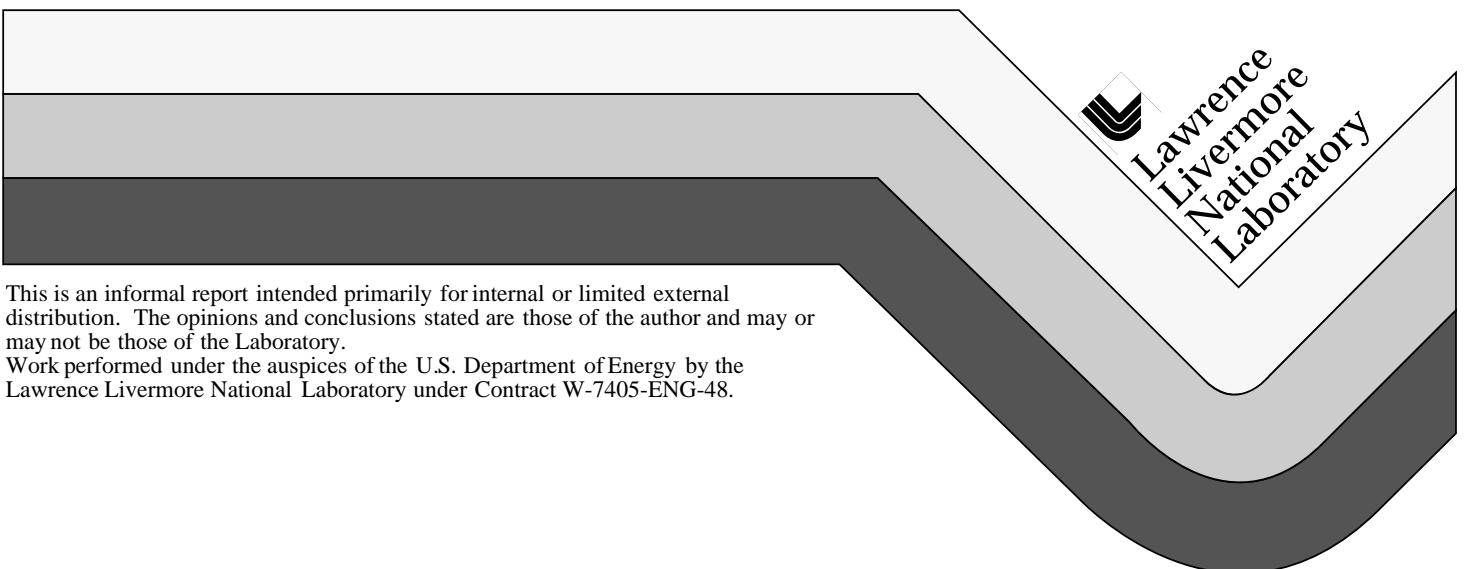


# Feasibility Study for Analyzing Plasma Aerodynamic Effects

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## LDRD Project Report

Project Title:

### **Feasibility Study for Analyzing Plasma-Aerodynamic Effects**

Category: ERD

Tracking Code: 98-FS-002

Principal Investigator: Bernie Penetrante, Physics Directorate

Co-Investigator: John Sherohman, NAI Directorate

## **Introduction**

For a number of years Russia has conducted a research and development effort aimed at utilizing non-conventional hypersonic technologies to achieve a significant breakthrough in hypersonic flight. The Russian program, known as Ajax, has the goal of building a Mach 12 or greater aircraft based on the integration of three novel subsystem technologies: plasma-aerodynamic shock-wave modification, endothermic fuel conversion, and magnetohydrodynamic (MHD) power generation. If successful, the integration of these technologies into the development of a hypersonic vehicle would revolutionize air and space flight.

There has been an awakening within the US aerodynamic community on the possibility that the novel technologies associated with the Ajax concept may have merit. In particular, plasma-aerodynamic experiments to modify shock wave behavior have generated much interest in the US aerodynamic community as well as internationally. This interest has been stimulated in large part from experimental work conducted at the Air Force Research Laboratory (AFRL), Wright-Patterson Air Force Base. The AFRL experiments have verified two major Russian claims: (1) that plasma-aerodynamic effects can cause "anomalous relaxation" of a bow shock wave, resulting in a major reduction in drag, and (2) that plasma effects can cause the speed of a shock wave to increase, the shock structure to disperse, and the shock wave amplitude to dissipate. Although verified experimentally, the phenomena are not understood. If these effects can be controlled and made to occur in an efficient, large-scale way, there is potential for high-payoff, both commercially and militarily.

In addition to reducing drag, the same plasma system could offer a fundamentally different type of stealth technology. It may be possible that aircraft can be made invisible to radar by creating plasma clouds around them. Several phenomena occur as the plasma cloud interacts with the electromagnetic waves. The waves are partly absorbed by the plasma as they interact with the charged particles in the cloud and transfer some of their energy to them. Electromagnetic waves also tend to bend around the plasma formation. Both these phenomena cause either a sharp decrease in signal reflection, or produce a number of false echoes that make it extremely difficult to determine the speed of the aircraft and its location.

## **Problem**

There are three types of plasma aerodynamics experiments that have been reported: (a) shock tube experiments [1-13], (b) ballistic experiments [14], and (c) wind tunnel experiments [15].

A shock tube experiment is shown schematically in Figure 1. The purpose of this type of experiment is to study the velocity and structure of a shock wave as it travels through a weakly-ionized ( $n_e/n = 10^{-6}$ ) plasma. Three main effects have been observed in shock tube experiments as the shock moves through the plasma: (1) the shock propagation velocity increases, (2) the shock amplitude decreases, and (3) the shock thickness increases.

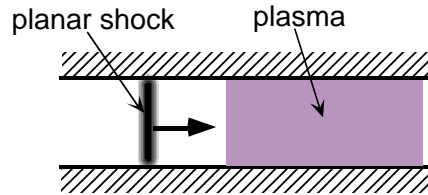


Figure 1. A shock tube experiment to study the interaction of a planar shock with a plasma.

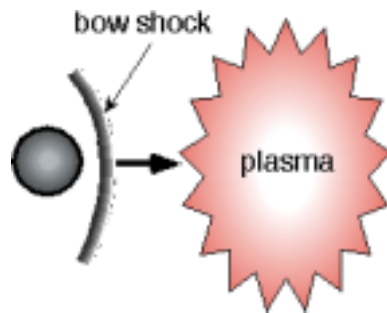


Figure 2. A ballistic experiment to study the drag and bow shock of a supersonic object moving through a plasma.

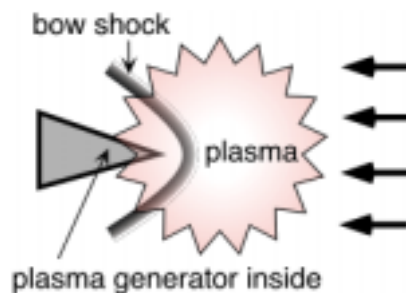


Figure 3. A wind tunnel experiment to study the drag and bow shock of a body with a built-in plasma generator.

A ballistic experiment and a wind tunnel experiment are shown schematically in Figures 2 and 3, respectively. The purpose of these types of experiments is to study the drag and bow shock of a supersonic object as it moves through a plasma. Two main effects have been observed in these experiments: (1) the shock standoff distance increases, and (2) the drag is reduced. The shock shape produced by an object travelling at high Mach number through a plasma is consistent with that for flight at low Mach number. Another interesting consequence of these effects is that the heat transfer to the flying object is potentially reduced.

The effects described above have been observed using different ionization methods and different shock wave generation techniques. The anomalous characteristics are present for different gases (air,  $H_2$ ,  $N_2$ ,  $CO_2$ , Ar, Ne, Xe, He) and different types of plasma-generating voltage waveforms (DC, RF). The effects are present, but there is controversy on what is causing these effects. The difference in opinion is the result of (a) lack of rigorous model for shock wave propagation in non-equilibrium, weakly-ionized plasmas, and (2) sparse database of carefully controlled experiments that can be used for model validation. Many experiments contain inhomogeneous gas temperature distributions. A temperature distribution can explain some of the experimental data, whereas other experiments cannot be explained by heating effects alone. Precise experiments are required to distinguish the “non-thermal plasma” effects from thermal gas effects.

The problem addressed in this project is the propagation of a shock wave through a weakly-ionized plasma in a shock tube. The shock tube experiment conducted at the Air Force Research Laboratory, Wright-Patterson Air Force Base, is the most carefully controlled and precise experiment available for validating physical models of the plasma aerodynamic phenomena [13]. A schematic of the shock tube experiment is shown in Figure 4. A longitudinal DC plasma is generated with a pair of electrodes inside a 5 cm diameter pyrex tube. An acoustic shock is generated by a spark gap. Photo-acoustic deflection waveform signals are simultaneously recorded at two or more locations. This experiment provides accurate measurements of both the shock velocity and the shock wave profile.

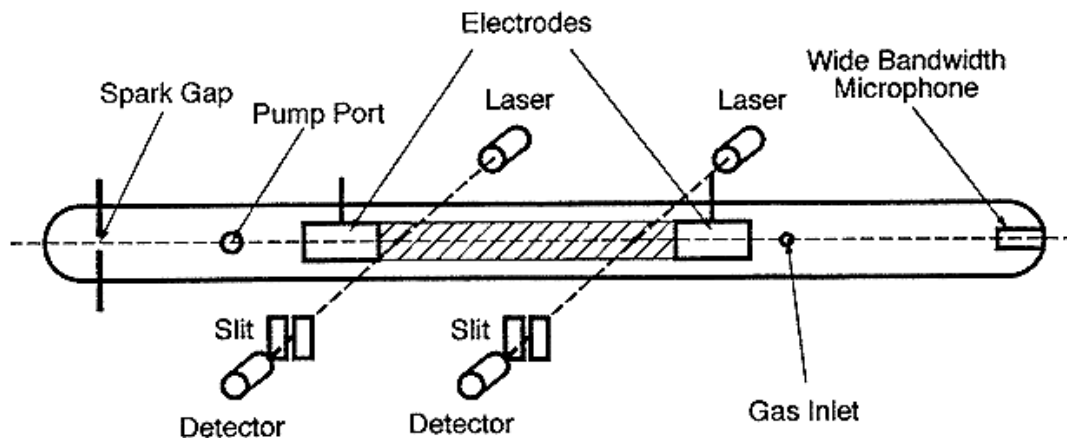


Figure 4. Schematic of the shock tube experiment conducted at the Air Force Research Laboratory, Wright-Patterson Air Force Base [13].

A sample of the opto-acoustic signals at a single location inside a 30 Torr argon discharge plasma is shown in Figure 5. The data shows three features as the electrical current in the plasma is increased: (a) the shock velocity increases (as noted from the decrease in arrival time at the same location), (b) the amplitude of the shock leading edge decreases, and (c) the dispersion of the shock waveform increases.

The results of the AFRL experiment confirm the effects reported by Russian scientists. However, the controversy remains on what physical mechanism is responsible for these effects. There is a lot of speculation. Some suggest that the energy exchange between the shock wave and the excited state atoms/molecules in the non-equilibrium plasma is important. Others suggest that a strong

space charge field is formed at the shock boundaries; ions get accelerated by the space charge layer and, by charge exchange collisions, transfer energy and momentum to neutrals in front of the shock wave.

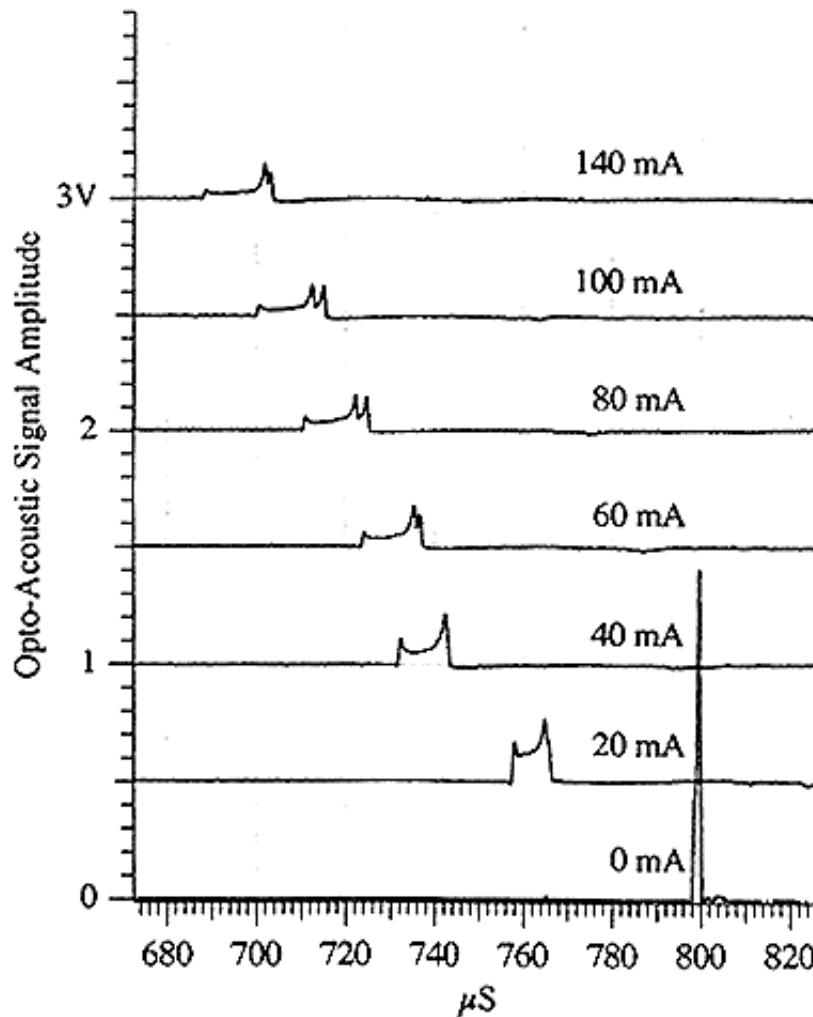


Figure 5. Shock induced opto-acoustic signals in a 30 Torr argon discharge plasma, taken 42 cm from the spark source [13].

## Objective

The purpose of this feasibility study was to conduct preliminary modeling to elucidate the mechanisms responsible for the effects observed in the AFRL shock tube experiment. It was assumed that the plasma is simply a region of gas in the shock tube that has a higher gas temperature. Computational fluid dynamics (CFD) calculations were performed to simulate the propagation of a shock wave through the tube, using the same parameters in the experiment. Both 1-D and 3-D CFD calculations were performed to determine which effects can be explained simply by axial temperature gradients and which effects require the presence of radial temperature gradients. Discharge plasma physics calculations of a longitudinal glow discharge were then used to establish if the electrical currents used in the experiment are consistent with the gas temperature distributions that are necessary to explain the observed effects.

## Results

The results of 1-D CFD calculations are shown in Figure 6. The 1-D calculations demonstrate several of the shock wave characteristics observed experimentally. As the gas temperature in the plasma region is increased, the shock velocity increases, as noted from the decrease in arrival time. The shock breaks up into multiple shocks as it encounters the temperature gradient between the plasma and the neutral gas. The amplitude of the leading shock decreases as the temperature in the plasma region is increased.

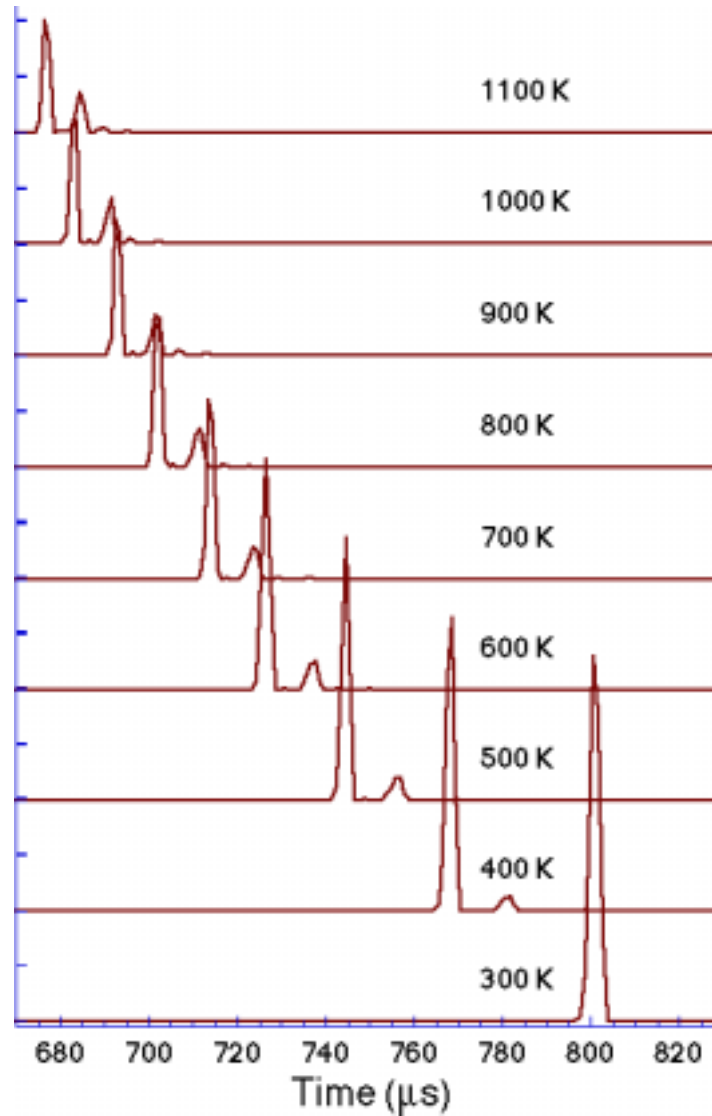


Figure 6. Calculated shock signals from 1-D model.

The 1-D results show that both the shock velocity increase and shock amplitude decrease could be explained by thermal gradients. However the 1-D calculations cannot explain the dispersion of the

shock wave structure. We therefore next examined how radial thermal gradients influence the shock wave damping.

The results of 3-D CFD calculations are shown in Figure 7. The temperature labels in the figure refer to the temperature along the longitudinal axis in the plasma region. The temperature boundary condition at the shock tube wall is assumed to be 300 K. The radially-averaged temperature in the plasma region is therefore much less than those indicated in Figure 7.

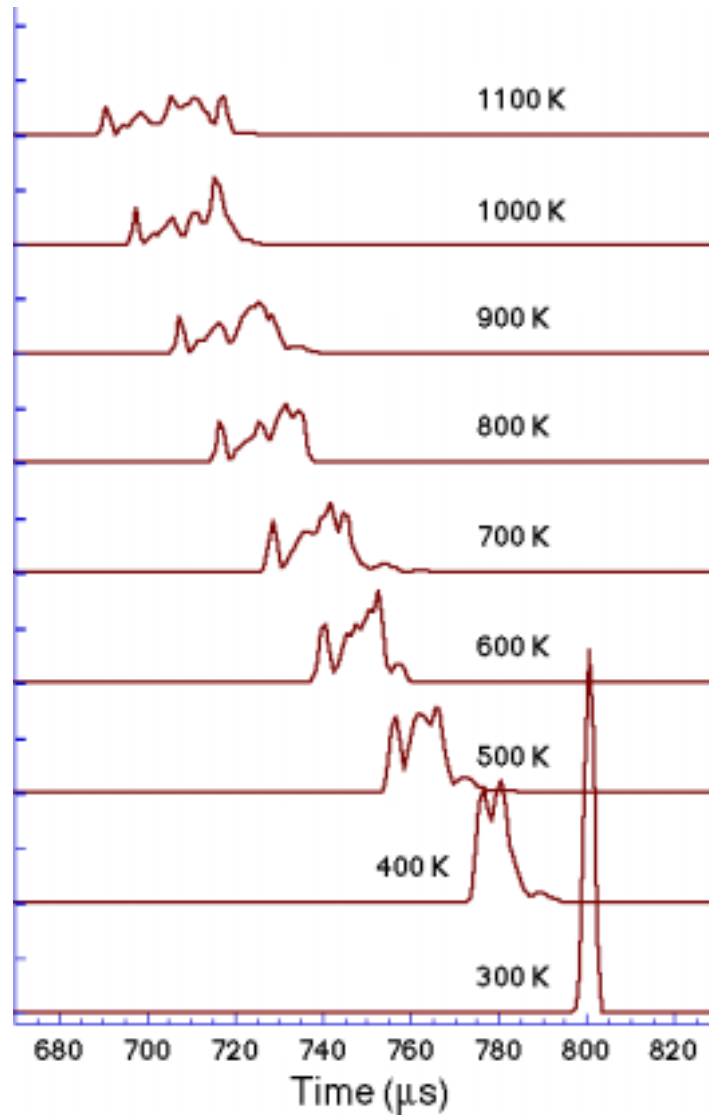


Figure 7. Calculated shock signals from 3-D model.

The 3-D results show that thermal gradients can explain all of the experimentally observed effects, including the dispersion and extreme damping of the shock wave structure. The gas temperatures required to quantitatively explain the experimental observations are consistent with those that are produced by the electrical currents used in the experiment.



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